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ScienceDirect
Procedia Engineering 10 (2011) 236–241
Engineering Procedia

ICM11

Analysis of damage events in quasi-isotropic laminates using a generalized micromechanics approach

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Abstract

Recently, the authors of paper developed a new micromechanics method to study the damage growth in laminated composites with different lay-ups. In this paper, the developed micromechanics approach is employed for the parametric analyses of four quasi isotropic laminates with [90/45/0/-45]s, [45/-45/0/90]s, [45/90/0/-45]s and [0/45/-45/90]s lay-ups under axial loadings. For this purpose energy release rate due to the transverse cracking and induced delamination are calculated and the order of damage happening in each laminate separately are discussed. The obtained results will be compared with the available experimental results.

Selection and peer-review under responsibility of ICM11
Keywords: Micromechanics; Transverse crack; Delamination; Quasi isotropic

1. Introduction

In the last decade, a great attention has been focused on investigating of matrix cracking, induced delamination and considering their influence on the thermo-mechanical behavior of laminates. A well known approach for this purpose is "*micromechanics method*". In this approach, the stress distribution of a composite in the presence of certain types of damage is analyzed. Among the available micromechanics methods, the most applicable approaches are shear lag method, variational principles and stress transfer mechanics [1]. As a general sense, the advantage of the available micromechanical based approaches is their strong physical meaning, but some of them are mainly limited to the analysis of cross-ply laminates under uniaxial tensile loading condition [1]. To overcome the weakness of the previously developed micromechanics approaches, recently, the authors developed a new micromechanics method to study the damage growth in laminated composites with different lay-ups. Using the developed micromechanics

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Selection and peer-review under responsibility of ICM11 doi:10.1016/j.proeng.2011.04.042

model the stress and displacement distributions in a desirable orthotropic single lamina containing transverse cracking and/or delamination is obtained. The novelty of this new method is the ability to be used for composite laminates with any lay-ups and any loading conditions. In this paper, the explained approach is employed for the parametric analyses of four quasi isotropic laminates with [90/45/0/-45]s, [45/-45/0/90]s, [45/90/0/-45]s and [0/45/-45/90]s lay-ups under axial loadings to calculate the energy release rate due to the transverse cracking and induced delamination and to examine the order of damage happening in each laminate separately.

2. Proposed micromechanics model

In this section a brief description of the developed micromechanics approach is explained. In this approach, a single lamina under general normal and shear stresses on all sides is considered which is prone for damage growth including matrix crack [2, 3] and induced delamination [4]. A generalized plane strain condition is considered for the cracked orthotropic composite lamina such that:

$$u = f(y,z) + \varepsilon_T^c x, v = v(y,z), w = w(y,z) \tag{1}$$

Furthermore, the stress and displacement fields are derived for a unit cell in the ply level with a specific crack density [3] and delamination length [4]. Having the stress and displacement equations for the damaged lamina, and combining with the constitutive equations, the following homogeneous simultaneous differential equations are obtained:

$$\begin{aligned} &F_i\phi''''(y) + G_i\phi''(y) + H_i\phi(y) = 0 \\ &S_i\psi''(y) + K_i\psi(y) = 0 \end{aligned} \tag{2}$$

By solving these differential equations and imposing appropriate boundary conditions including stress free conditions at the crack surfaces as presented in the following equations, the $\phi(y)$ and $\psi(y)$ functions can be calculated[3].

$$\sigma_{yy}(\pm L,z) = 0, \sigma_{yx}(\pm L,z) = 0, \sigma_{yz}(\pm L,z) = 0 \tag{3}$$

Based on the obtained stress field, the energy release rates for further matrix cracking and its induced delamination are calculated. The expressions $\int\sigma\varepsilon(\rho)dV$ and $\int\sigma\varepsilon dV$ define the strain energy for cracked lamina with ρ crack density and strain energy of undamaged lamina respectively.

$$\left(\int\sigma\varepsilon(\rho)dV - \int\sigma\varepsilon dV - G_{mc}\times A\right) > 0 \tag{4}$$

3. Nonlinear finite element code

Furthermore the authors of this paper developed an available home CDM finite element code [3]. In this code, 8 nodes full layer-wise elements are used. For modeling of the nonlinear response due to damage initiation and growth, the developed micromechanics approach by the present authors is used. This procedure is employed in an extended subroutine for developing a proposed damage flow rule and numerical integration of constitutive relations. In this subroutine, having the boundary conditions and using the developed micromechanics approach, the stress and strain fields of the cracked unit cell and the strain energy release rate can be obtained. The obtained strain energy release rate is compared with finite fracture toughness of lamina, Gc, to recognize the evolution of transverse matrix crack density and/or delamination length at each element. Details of this nonlinear FE code were presented in [2, 3].

4. Results and Discussions

In this section, the explained micromechanics approach is employed for the analysis of four quasi-isotropic Carbon/Epoxy laminates with E_x = 128 GPa, E_y = 7.2 GPa, G_{xy} = 4 GPa, m_{xy} = 0.3 and Gc = 175

J/m^2 [4] under in-plane axial force of 91.5 N. The in-plane stresses due to this loading before occurrence of damages are obtained from classical theory for each layer and employed as remote stresses for each unit cell layer. Therefore, the in-plane axial stress of σ_x=230 MPa, in-plane transverse stress of σ_y=-0.05 MPa and shear stress of τ_{xy}=0 are considered for 0° ply, 81MPa, 7 MPa, 10 MPa for 45° ply, 81MPa, 7 MPa, -10 MPa for -45° ply and -68MPa, 14 MPa, 0 for 90° ply respectively. The energy release rates versus crack density for transverse cracking and delamination are calculated for the 90°, 45° and -45° plies and compared with the FEM results for [90/45/0/-45]s in Fig 1. This figure shows that the predicted energy release rates are in good agreement with the FEM results.

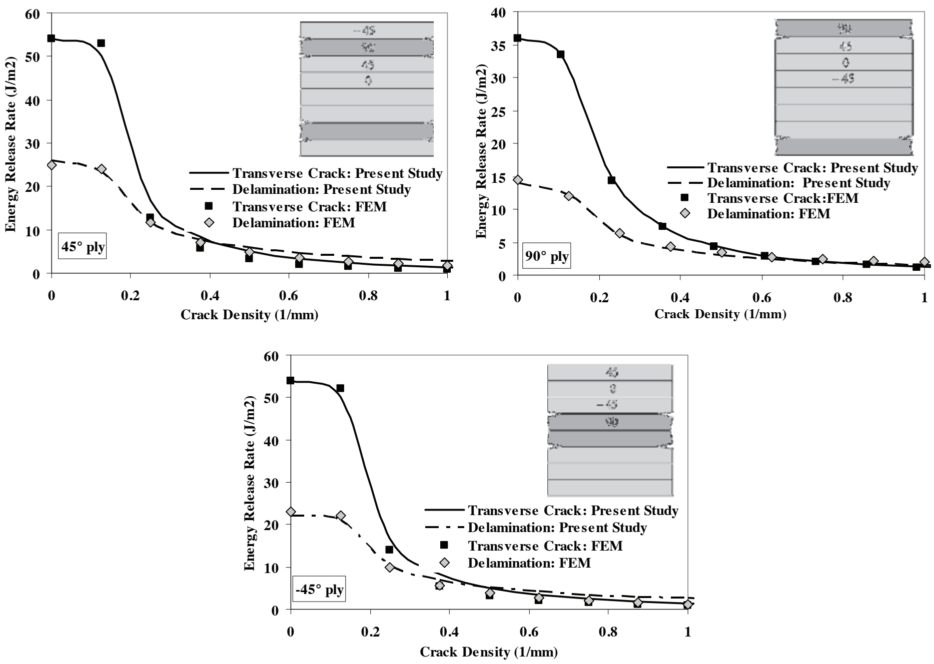

Fig. 1. Comparison of the obtained energy release rate versus crack density for transverse cracking and induced delamination with FEM results for [90/45/0/_45]s Carbon/Epoxy laminate

It also shows that for transverse crack formation, the 45° and -45° plies release more strain energy than 90° ply. Therefore, transverse cracking is firstly occurred in 45° and -45° plies and then 90° ply is prone for transverse crack formation. The obtained results for induced delamination show that after transverse crack formation in these plies, 45° ply is more susceptible for delamination initiation than 90° and -45° plies. Variations of energy release rate versus crack density for transverse cracking and delamination are intersected at the crack density of 0.8 (1/mm) for 90° ply, 0.52 (1/mm) for -45° ply and 0.41 (1/mm) for 45° ply respectively showing the happening of dominant delamination damage after these points. The available experimental results for this quasi-isotropic laminate [5] justify the happening of transverse cracking at 45° and -45° plies firstly and then induced delamination initiation at interface of 45°/0° plies.

Using the proposed micromechanics approach, damage mechanism (Transverse cracking and delamination) are predicted for three different quasi-isotropic laminates of [45/-45/0/90]s, [45/90/0/-45]s and [0/45/-45/90]s under the same above described loading condition for [90/45/0/-45]s laminate. Because of the same loading condition in each laminate, the strain energy release rate for transverse crack formation is equal in the namesake layers.

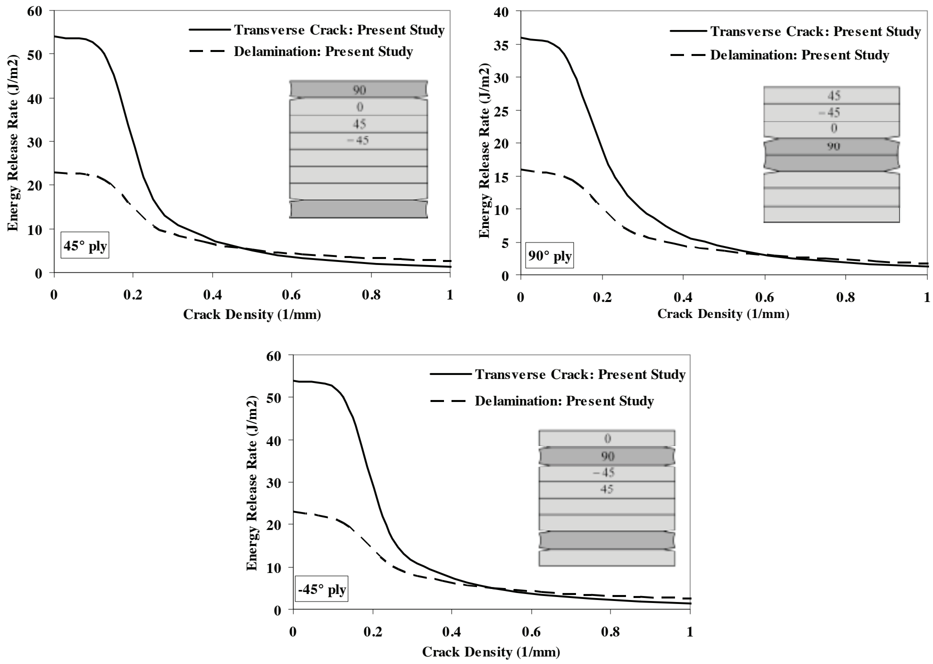

Fig. 2. Comparison of the obtained energy release rate versus crack density for transverse cracking and induced delamination with FEM results for [45/-45/0/90]s Carbon/Epoxy laminate

The obtained induced delamination results for [45/-45/0/90]s laminate in Fig.2 show that after crack formation, the -45º ply is more susceptible for delamination initiation than 90º and 45º plies. Variations of energy release rate versus crack density for transverse cracking and delamination are intersected at the crack density of 0.65 (1/mm) for 90 º ply, 0.51 (1/mm) for -45º ply and 0.53 (1/mm) for 45º ply respectively. The available experimental results for this quasi-isotropic laminate [5] justify the happening of transverse cracking at -45º ply at first and the induced delamination initiation at interface of -45º/0º plies. The obtained induced delamination results for [0/45/-45/90]s laminate in Fig. 3 show that after transverse crack formation, the 45º ply is more susceptible for delamination initiation than 90º and -45º plies. Variations of energy release rate versus crack density for transverse cracking and delamination are intersected at the crack density of 0.62 (1/mm) for 90 º ply, 0.6 (1/mm) for -45 º ply and 0.5 (1/mm) for 45 º ply respectively. Fig. 4 also shows the obtained results for induced delamination in [45/90/0/-45]s laminate. This figure verifies that after transverse crack formation, the 90º ply is more susceptible for delamination initiation than 45º and -45º plies. Variations of energy release rate versus crack density for transverse cracking and delamination are intersected at the crack density of 0.6 (1/mm) for 90 º ply, 0.65(1/mm) for -45º ply and 0.85 (1/mm) for 45º ply respectively. The experimental observations in [5] verify the predicted behavior.

At last, the developed CDM code [3] is employed to evaluate the stress-strain behavior for these laminates. The obtained global stress-strain behaviors for various laminates are identical but the circumstances of damage happening are different for each lay-up configuration. Also, the obtained results by CDM code justify the state of transverse crack and induced delamination growth in each laminates.

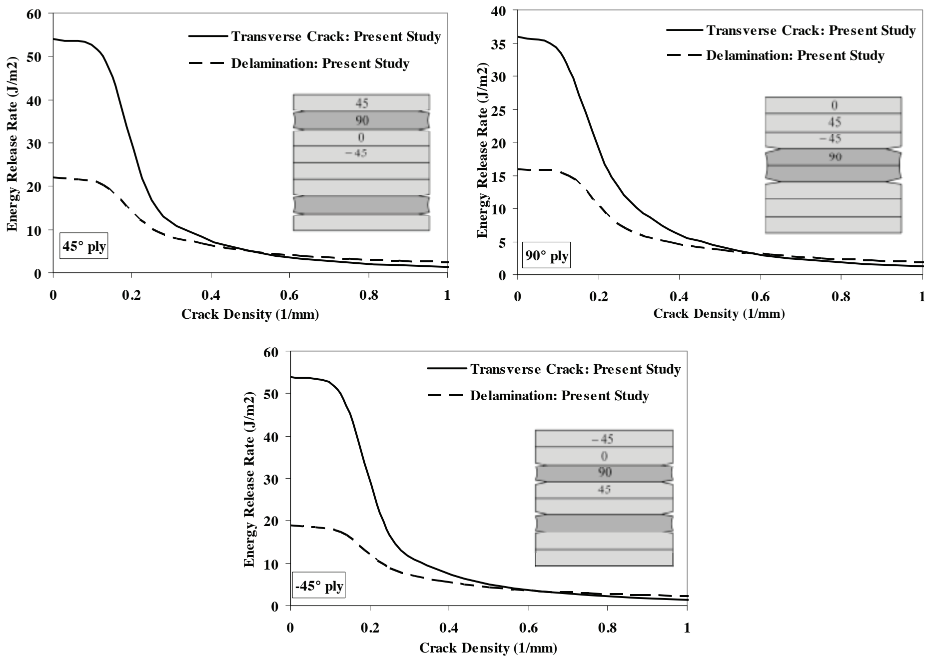

Fig. 3. Comparison of the obtained energy release rate versus crack density for transverse cracking and induced delamination with FEM results for [0/45/-45/90]s Carbon/Epoxy laminate

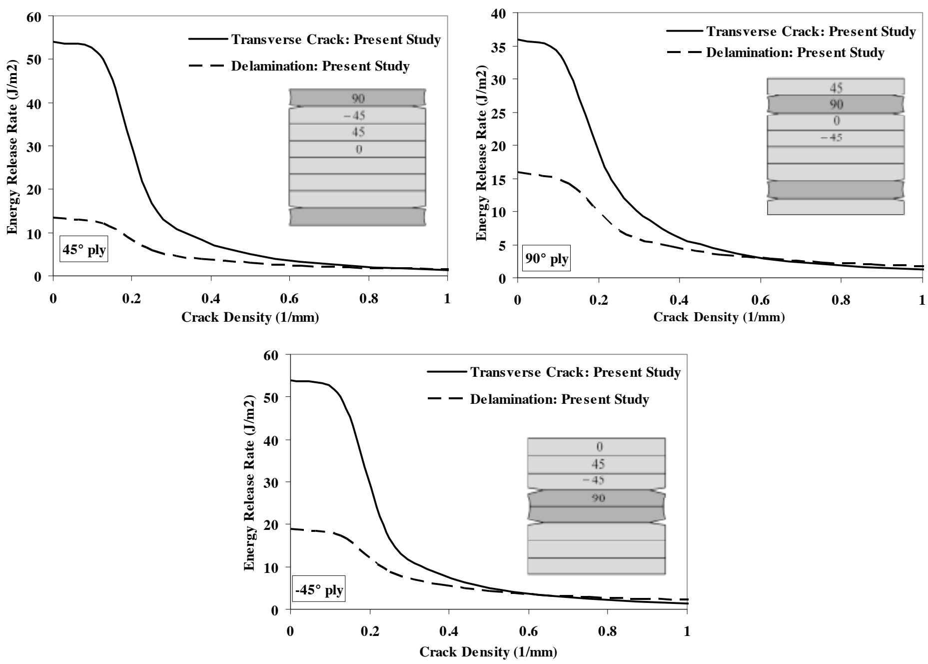

Fig. 4. Comparison of the obtained energy release rate versus crack density for transverse cracking and induced delamination with FEM results for [45/90/0/-45]s Carbon/Epoxy laminate

Fig. 5 shows the stress–strain behavior for [0/45/-45/90]s laminates under the uniaxial tension loading. The predicted stress–strain behavior is in a good agreement with the experimental results [6] for both initiation and propagation of the transverse cracks and induced delamination up to the final failure load of laminate. The performed analyses and acceptable results for quasi-isotropic laminates show that the presented micromechanics approach can be used to estimate the energy release rate due to the transverse cracking and induced delamination for laminates with any lay-ups under combined in-plane loadings. However, previously developed micromechanical approaches limited to the analysis of laminates with the specific lay-ups such as cross-ply and specific loading conditions.

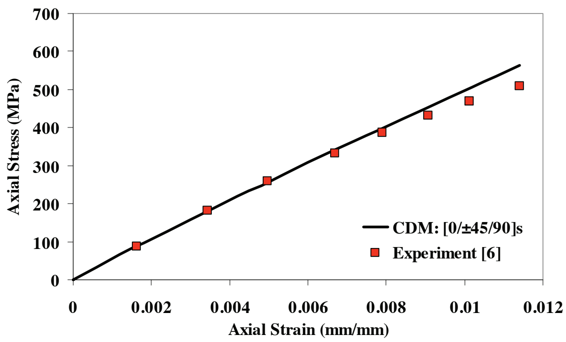

Fig. 5. Comparison of the obtained stress-strain behavior for [0/45/-45/90]s laminate with experimental results

5. Conclusion

The developed new micromechanics approach was used for the analyses of several quasi isotropic laminates under combined loadings to calculate the energy release rates due to transverse cracking and induced delamination. It was shown that the recently developed micromechanical approach by the authors predicts the damage mechanisms of different quasi-isotropic laminates with acceptable accuracy. The predicted stress-strain behavior by CDM also verified the sequence of damage mechanisms happening obtained from the micromechanics approach.

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